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Applications of Turbidity Monitoring to Forest Management in California

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Abstract Many California streams have been adversely affected by sedimentation caused by historic and current land uses, including timber harvesting. The impacts of timber harvesting and logging transportation systems on erosion and sediment delivery can be directly measured, modeled, or inferred from water quality measurements. California regulatory agencies, researchers, and land owners have adopted turbidity monitoring to determine effects of forest management practices on suspended sediment loads and water quality at watershed, project, and site scales. Watershed-scale trends in sediment discharge and responses to current forest practices may be estimated from data collected at automated sampling stations that measure turbidity, stream flow, suspended sediment concentrations, and other water quality parameters. Future results from these studies will provide a basis for assessing the effectiveness of modern forest practice regulations in protecting water quality. At the project scale, manual sampling of water column turbidity during high stream flow events within and downstream from active timber harvest plans can identify emerging sediment sources. Remedial actions can then be taken by managers to prevent or mitigate water quality impacts. At the site scale, manual turbidity sampling during storms or high stream flow events at sites located upstream and downstream from new, upgraded, or decommissioned stream crossings has proven to be a valuable way to determine whether measures taken to prevent post-construction erosion and sediment production are effective. Turbidity monitoring at the project and site scales is therefore an important tool for adaptive management. Uncertainty regarding the effects of current forest practices must be resolved through watershed-scale experiments. In the short term, this uncertainty will stimulate increased use of project and site-scale monitoring.

Keywords Turbidity · Suspended sediment · Monitoring · Forest management · California

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The impacts of timber harvesting on erosion and sedimentation in forest streams have been recognized for decades (Ice and Stednik 2004). Excessive stream sediment loads can adversely affect fish habitat, fish feeding, levels of adsorbed pollutants, and municipal water supply treatment costs (Bisson and Bilby 1982, Henley and others 2000, Rehg and others 2005). Approaches for quantifying timber harvest-related erosion and sediment production include direct measurement (Croke and Mockler 2001, MacDonald and others 2001, Sidle and others 2004), modeling (Elliot and others 1995, Croke and Nethery 2006, Forsyth and others 2006), and experiments with simulated rainfall (Croke and others 1999). Forest management

effects may be indirectly inferred from water quality data (Ice and Stednik 2004).

Recently, stream turbidity monitoring has gained increased acceptance as a tool for estimating forest management-related sediment production and delivery to streams. Turbidity is an expression of optical properties that cause light to be scattered or absorbed by suspended particles in water. It is most commonly reported in nephelometric turbidity units (NTU), although other units are also used (Anderson 2004). Turbidity is relatively easy to measure as compared to suspended sediment concentration (SSC), and with sufficient data it is feasible to develop strong statistical correlations between turbidity and SSC within a stream (Beschta 1980, MacDonald and others 1991, Lewis 1996).

Turbidity measurements are used to construct sediment records for estimating annual or storm event sediment yield, and to detect specific events, such as a flush of sediment into a stream during a storm (Beschta 1987, Lewis 1996, Cornish 2001, Anderson 2004, Chappell and others 2004). Both turbidity and SSC are subject to extreme variability from storm to storm and from year to year. In the context of experimental studies or project monitoring and impact assessment, this variability must be addressed with long-term data sets, experimental designs such as a before-after-control-impact or ''BACI'' approach (Stewart-Oaten and others 1986, Walters and others 1988, Lewis and others 2001), or simultaneous above–below measurements at specific sites (MacDonald and others 1991, Lane and Sheridan 2002).

Turbidity monitoring has been widely adopted in California to evaluate impacts of timber harvest operations. In this paper, we provide an overview of ongoing turbidity monitoring studies in the state, including a discussion of experimental designs and methods being used at the watershed, project, and site scales. Many of the current studies were started recently and to date, few results from this work have reached the published literature. We omit discussion of equipment selection and use, data interpretation, or quality control here because these topics are covered in detail elsewhere (e.g., Gippel 1995, USEPA 1999, Edwards and Glysson 1999, Eads and Lewis 2002, Anderson 2004, Wagner and others 2006). In presenting this review, it is our intent to evoke interest in the use of turbidity monitoring in forest environmental regulation and adaptive management.

Regulation of Timber Harvesting: The Impetus for Monitoring

California forestlands are geologically diverse. Natural erosion rates are low to moderate in the Sierra Nevada but are among the highest in world in the wetter, tectonically active coastal watersheds (Brown and Ritter 1971, Kelsey 1980). Many coastal streams where forest management is a current or past land use have been designated by the U.S. Environmental Protection Agency (USEPA) as sediment impaired pursuant to Section 303(d) of the Federal Clean Water Act. In addition, the ranges of some anadromous salmonids listed as Threatened or Endangered under Federal and State Endangered Species Acts include the entire commercial forest area of coastal California (Fig. 1).

Timber harvesting in California is subject to a comprehensive body of regulations that is enforced by the California Department of Forestry and Fire Protection (CDF). Except for emergency and minor logging operations, a Timber Harvesting Plan (THP) or equivalent permit is required for harvesting, road construction or improvement, and follow-up timber operations such as site preparation and restocking. A THP may range in area from tens to thousands of hectares. Each THP is prepared by a state-licensed Registered Professional Forester and goes through a multiagency environmental review process with CDF acting as the lead agency. There are approximately 200 field-oriented rule requirements that apply to erosion control and sediment production from timber harvest sites (Cafferata and Munn 2002).

Fig. 1 Boundaries of area affected by federally listed threatened and endangered salmonids in coastal California (Mapping by Chris Keithley, California Department of Forestry and Fire Protection, Sacramento, CA)

Timber harvesting and associated management are also subject to water pollution control rules developed by Regional Water Quality Control Boards (RWQCB) pursuant to Federal and State water pollution control laws. RWQCB staff engage in the THP multiagency review process and may, at their discretion, impose permit conditions (e.g., restoration projects, watershed investigations, and water quality monitoring) on a project-by-project basis to ensure that water quality is protected.

Compliance with State and Federal Endangered Species Acts on a THP-by-THP basis can be both expensive and time consuming. To streamline this process, some commercial timber companies have developed a Habitat Conservation Plan (HCP) or other management agreement with Federal and State agencies to meet legal requirements for protecting endangered species. A HCP that addresses listed salmonids will often include measures to prevent sedimentation and requirements for monitoring water quality or watershed conditions.

The requirements of the forest practice rules, water quality control regulations, and Endangered Species Acts have all stimulated a recent increase in water quality monitoring on forest lands at watershed, project, and site scales. Turbidity monitoring has become a popular tool for evaluating the effects of timber harvesting on stream suspended sediment loads.

Overview of Turbidity Monitoring in California

In the winter and spring of 2005–2006, the authors conducted a survey of landowners and agencies in California to determine where turbidity monitoring was occurring in forested watersheds. As of March 2006, studies were under way or had been recently completed in 27 major watersheds in the California Coast Range and the Sierra Nevada (Fig. 2 and Table 1). In two watersheds (Elk River and Freshwater Creek in Humboldt County), studies were being done at all three scales by organizations with different objectives. With the exception of the longer term Caspar Creek research project described in the next section, all studies began or took place within the past decade.

Studies listed in Table 1 are only those that directly involve assessments or evaluations of forested watersheds subject to timber harvesting or other forest management activities. Numerous additional studies that evaluate other land management activities are not listed. For example, most municipal water companies in California are required to collect water quality data, including turbidity measurements, at their collection and storage facilities. Turbidity monitoring is also a commonly required condition for urban development permits at major construction sites located at or near water bodies.

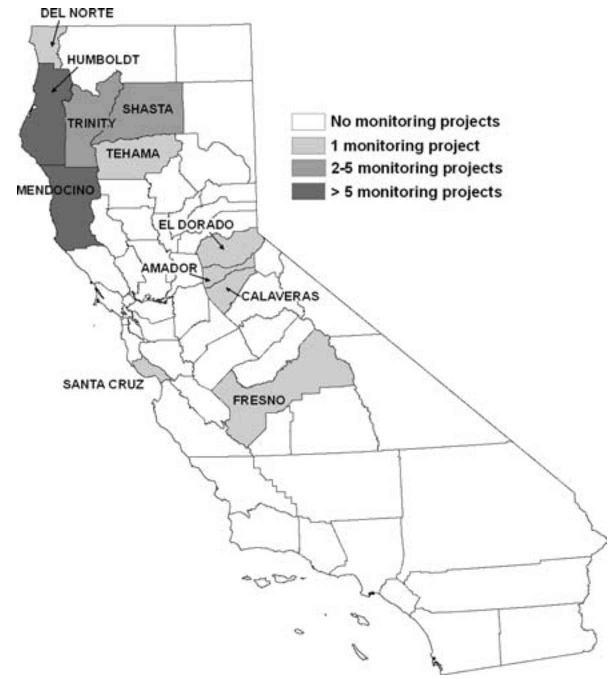

Fig. 2 Stream turbidity monitoring projects in California forested watersheds, March 2006 (Mapping by Suzanne Lang, California Department of Forestry and Fire Protection, Santa Rosa, CA)

Turbidity Monitoring at the Watershed Scale

Turbidity monitoring studies at the watershed scale are occurring in most of the forest ecoregions of the state (Table 1). These studies are conducted by a variety of agencies, companies, universities, and nongovernmental organizations. Some are supported by a combination of public and private funding.

None of the watersheds listed in Table 1 would be considered pristine, and most have been affected by more than 100 years of land use. In some of these watersheds, sediment yields may be 20–700% greater than natural levels (Sullivan, unpublished data). Unnaturally high and extremely variable sediment loads present design challenges to experimental studies attempting to detect potentially subtle changes in sedimentation due to improved forest practices. Trend-monitoring studies are similarly challenged. What might be perceived as a positive change in sediment loads or stream habitat due to improved watershed conditions can be quickly reversed during an extreme event that mobilizes large amounts of temporarily stabilized sediment (Madej 1999).

Experimental Design

Seven studies were designed to test the effects on suspended sediment loads of timber harvesting subject to California Forest Practice Rules. Three studies (Caspar

Table 1 Turbidity monitoring studies in California forested watersheds as of March 2006

County	Watershed	Monitoring entities	Objectives	Time frame	Website	References
Amador	Antelope Creek	Central Valley Regional Water Quality Control Board (CVRWQCB)	■ Project-scale timber harvest effects ■ Site-scale stream crossing effects	WY 2004		CVRWQCB (2004)
Calaveras	San Antonio Creek	Sierra Pacific Industries (SPI)	Watershed-scale trend detection	WY 2001 to present	12	
Del Norte	Little Jones Creek	U.S.D.A. Forest Service (USFS)	Watershed-scale fish population modeling	WY 2000 to present	1	
El Dorado	Angora Creek	El Dorado County	Watershed-scale trend detection	WY 2003 to present		
Fresno	North Fork Kings River tributaries (KREW)	USFS	Watershed-scale experimental design, logging and prescribed fire	WY 2006 to present (turbidity)	11	Hunsaker and Eagan (2003)
Humboldt	S.F. Eel River, Bull and Cuneo Creeks	USFS	Watershed-scale fish population modeling	WY 2005 to present		
Humboldt	S.F. Eel River, Canoe and Decker Creeks	California State Parks	Watershed-scale trend detection	WY 2004 to present		
Humboldt	Little River, Maple Creek tributaries	Green Diamond Resource Company	Watershed-scale trend detection	WY 2002 to present	4	
Humboldt	Elk River and tributaries	■ Pacific Lumber Company (PALCO) ■ Salmon Forever ■ Humboldt State University ■ Pacific Watershed Associates ■ California Department of Fish and Game ■ Green Diamond Resource Company	■ Watershed-scale trend detection ■ Project-scale timber harvest and road effects ■ Site-scale stream crossing effects	WY 2003 to present	5,7,14	PALCO (2004), Manka (2005), Pacific Watershed Associates (2005)
Humboldt	Freshwater Creek and tributaries	■ Pacific Lumber Company (PALCO) ■ Salmon Forever ■ Humboldt State University ■ Pacific Watershed Associates ■ California Department of Fish and Game ■ Green Diamond Resource Company	■ Watershed-scale trend detection ■ Project-scale timber harvest and road effects ■ Site-scale stream crossing effects	WY 1999 to present	5,6, 14	PALCO (2004)
Humboldt	Eel River, Bear and Jordan Creeks	PALCO	Watershed-scale trend detection	WY 2004 to present		
Humboldt	Jacoby Creek	■ USFS ■ Jacoby Creek Land Trust	■ Watershed-scale fish population modeling ■ Trend detection	WY 2001 to present	8	

Table 1 continued

County	Watershed	Monitoring entities	Objectives	Time frame	Website	References
Humboldt	Mattole River tributaries	Sanctuary Forest	Site-scale stream crossing effects	WY 2003	17	Klein (2003)
Humboldt	Redwood Creek and tributaries	■ Redwood National/State Parks	■ Watershed-scale trend detection	WY 2001 to present	16	Klein (2006)
		■ University of California	■ Site-scale stream crossing effects			Weaver and others (2005)
Humboldt	Mad River tributaries	U.S. Environmental Protection Agency	Watershed-scale trend detection	WY 2006-WY 2007		
Mendocino	Caspar Creek-North and South Forks + tributaries	USFS and CDF	Watershed-scale experimental design, logging and road effects	WY 1963 to present	2	Lewis and others (2001), Ziemer (1998)
Mendocino	Garcia River tributaries	Mendocino County Resource Conservation District and CDF	Watershed-scale trend detection	WY 2004, WY 2005	3	Barber and Birkas (2005)
Mendocino	South Fork Ten Mile River tributaries	Campbell Timberland Management	Watershed-scale trend detection	WY 2002 to present		
Mendocino	S.F. Eel River, Elder Creek	USFS	Watershed-scale fish population modeling	WY 2006 forward		
Mendocino	Russian River, Parsons Creek	University of California	Site-scale stream crossing effects	WY 2004	16	Weaver and others (2005)
Mendocino	S.F. Wages Creek	Campbell Timberland Management and CDF	Watershed-scale experimental design, logging and road effects	WY 2004 to present	13	Graham Mathews Associates (2004)
Santa Cruz	Little Creek and tributaries	California Polytechnical University, San Luis Obispo and CDF	Watershed-scale experimental design, logging and road effects	WY 2001 to present	9	
Shasta	Clear Creek	Western Shasta Resource Conservation District	Watershed-scale restoration effectiveness monitoring	WY 2004 to present	18	
Shasta	Millseat Creek	SPI	Watershed-scale experimental design, logging and road effects	WY 1999 to present		
Shasta	Bailey Creek	SPI	Watershed-scale experimental design, logging and road effects	WY 2002 to present		
Shasta	Hazel Creek	SPI	Watershed-scale experimental design, logging and road effects	WY 2002 to present		
Tehama	Judd Creek	SPI and CDF	Watershed-scale experimental design, logging and road effects	WY 2001 to present	15	James (2004)
Trinity	Trinity, Klamath River tributaries	Hoopa Valley Tribe	Watershed-scale trend detection	WY 1998 to present	10	

Table 1 continued

County	Watershed	Monitoring entities	Objectives	Time frame	Website	References
Trinity	Rush Creek, Indian Creek, Trinity River	US Bureau of Reclamation	Watershed-scale restoration effectiveness monitoring	WY 2004 to present		

Websites:
1 http://www.fs.fed.us/psw/topics/water/tts/little_jones/
2 http://www.fs.fed.us/psw/topics/water/caspar/
3 http://www.bof.fire.ca.gov/board/garcia_final_comments.pdf
4 http://www.greendiamond.com/environment/fisheries.asp#Stream_Habitat_Assessment_and_Monitoring
5 http://www.palco.com/commitment_scientific_qual_tmdl.cfm
6 http://www.salmonforever.net/
7 http://www.humboldt.edu/~egr2/documents/MankaThesis.pdf
8 http://www.fs.fed.us/psw/topics/water/tts/upper_jacoby/
9 http://ari.calpoly.edu/images/46670%20Dietterick%20Final.doc
10 http://www.hoopa-nsn.gov/departments/tepa/waterquality.htm#Temperature
11 http://www.fs.fed.us/psw/programs/snrc/water/kingsriver/
12 http://www.spi-ind.com/Our_Forests/Upper_San_Antonio_Crk.htm
13 http://www.bof.fire.ca.gov/pdfs/SFWages_EffectivenessProposal_Nov2004.pdf
14 http://www.palco.com/commitment_scientific_qual_timber.cfm
15 http://www.bof.fire.ca.gov/pdfs/Judd%20Creek%20Final_Prospectus_MSG_maps.pdf
16 http://forestry.berkeley.edu/comp_proj/dfg.html
17 http://www.bof.fire.ca.gov/pdfs/RKleinSanctSept2003.pdf
18 http://www.westernshastarcd.org

Creek, South Fork Wages Creek, and Little Creek; Table 1) have a BACI design. The others have ''before–after'' designs (all Sierra Pacific Industries projects; Table 1). Twelve ''trend detection'' studies are monitoring turbidity to estimate sediment discharge over time without attempting to separate out the effects of upstream land uses. Other studies monitor fish population responses to sediment loads (three studies being conducted by the U.S. Forest Service), effects of wildfire and prescribed fire treatments (the Kings River watershed study), and watershed restoration effectiveness (Clear Creek, Trinity River and its tributaries).

Data Collection Methods

All watershed-scale studies in California now use automated sampling stations that continuously measure sediment and stream flow over time. Stream flow and sediment at these sites are measured in a straight stable channel reach or a flume rated for discharge. After an initial period of measuring both discharge and stream stage (i.e., flow depth), a stage-discharge regression is created. Thereafter, only stage is measured with a pressure transducer, gas bubbler, or float unless channel changes require development of a new stage-discharge relationship. Turbidity is measured with a turbidimeter submerged in the water column above the zone of bedload transport. Where SSC data are needed, an automatic pumping sampler collects water samples taken from the field for laboratory analysis. A programmable data logger controls the sampling equipment and records the data. If study objectives include estimating total sediment yield, bedload measurements are required (Lewis 1998). Bedload measurement is very difficult, so few studies attempt it. Manual discharge and depth integrated sediment samples are taken for calibration with samples taken automatically. If streams are deeper than about 0.75 m at bankfull discharge or if wading during high flow is too dangerous, a bridge, platform, or cableway is required for collecting these samples.

There have been difficulties installing and operating automated stations on smaller streams in at least one California study (South Fork Wages Creek). Smaller streams in headwater areas may have flashy hydrographs with extreme peaks carrying high bedload and very low summertime flows. When bedload is moving, turbidity probes may be buried and give spurious measurements. When flows are low, probes may not be fully submerged (Faucher, unpublished data). Frequent site visits, often during dangerous weather, are required to address these problems.

Simultaneous measurements can be used to establish a regression between SSC and turbidity for prediction of sediment yields from turbidity measurements alone. To

create a stable and statistically acceptable regression, there must be sufficient numbers of SSC and matching turbidity samples that span the full range of concentrations experienced at different flows (MacDonald and others 1991). The correlation between turbidity and SSC tends to be strongest in watersheds with fine-grained sediments (Lewis and Eads 2001).

Developing the turbidity-SSC relationship for a particular station may require long-term sampling. It is common for SSC to range two to three orders of magnitude over the course of the water year in many California rivers and streams. SSC is subject to both within-year and between-year variability (Beschta 1987, Tate and others 1999, Ziegler 2003). SSC concentrations may be different at the same discharge on rising and falling limbs of the storm hydrograph (hysteresis). To account for all these sources of variability, SSC-turbidity relationships are developed for each sampling station on both an annual and storm-by-storm basis.

Before the introduction of turbidimeters, correlations between continuously recorded stream flow and SSC samples obtained with pumping samplers were used to estimate total annual sediment yield. Turbidimeters can provide thousands of data points at each site rather than the hundreds of SSC samples that were possible when only pumping samplers were used. These additional data points help account for previously unmeasurable variations in sediment concentrations, enabling the development of superior sediment yield estimates and more detailed analysis of sediment transport dynamics.

Some California watershed studies base the timing of SSC sampling on Turbidity Threshold Sampling, or TTS protocols (Lewis and Eads 2001, Lewis 2002). TTS relies on a program loaded into a data logger that triggers an automated pumping sampler to collect SSC samples, with an increasing probability of taking a sample as turbidity levels rise. This program ensures that the entire range of sediment concentrations is sampled while minimizing the number of SSC samples that must be analyzed to establish a reliable SSC/turbidity relationship (Lewis and Eads 2001).

Several turbidimeters are available for use in stream and river environments (see Web sites listed in Table 1 for design details and equipment choices used in California studies). Each manufacturer has its own unique approach to measuring optical parameters. This leads to differences in reported turbidity values even among laboratory turbidimeters. Consequently, it is critical to record the type of instrument used when reporting turbidity data (Davies-Colley and Smith 2001, Ankcorn 2003, Ziegler 2003, Anderson 2004). To improve data comparability, some watershed studies calibrate field turbidimeter measurements to one laboratory instrument for reporting purposes (Sullivan, unpublished data). Differences between devices can be critical when turbidity values are used as regulatory standards.

Case Study: The Caspar Creek Watershed Study

The Caspar Creek study has been measuring stream flow and suspended sediment transport since 1963 in a northwestern California coastal watershed. The study area has measurement stations on 21 watersheds ranging in size from 10 to 217 ha nested within two larger watersheds of approximately 500 ha each. The primary objective of the Caspar Creek study is to determine the response of stream flow and sediment discharge to logging and road construction. The project has a BACI design with multiple control and treatment watersheds repeatedly measured before and after disturbance. Management effects have been documented during two separate periods of logging, with the first beginning in 1968 and the second beginning in 1989. Over the course of the study, the Caspar Creek area has experienced large storms but not an extreme event (e.g., greater than 20-year recurrence interval).

Ziemer (1998) presents a compendium of papers about the Caspar Creek study. Recent summaries of some results are also available (Lewis and others 2001, Rice and others 2004). Generally, the first phase of the study found that selective tractor logging and road construction in the South Fork of Caspar Creek caused a threefold increase in suspended sediment loads in streams draining treated watersheds (Lewis and others 2001). Sediment increases caused by the second phase of logging (beginning in 1989), when nearly half of the North Fork Caspar Creek watershed was clear-cut, were statistically significant but smaller (Lewis 1998). The differences in impact were attributed at least partially to changes in forest practice regulations after 1973 that required a higher level of water quality protection. Future phases of the study will evaluate the effects of harvesting and road construction under the more stringent forest practice regulations adopted after 1990.

Researchers at Caspar Creek have implemented improvements to measurement methods and sampling procedures over the course of the study. These included installation of automatic pumping samplers in the 1980s and *in situ* turbidimeters in the 1990s. Pumping samplers already proved their value in the interpretation of management impacts during the North Fork phase of the study (Lewis 1996, 1998). The ability to estimate SSC was enhanced by the development and implementation of TTS as an alternative to discharge-driven probability sampling. It is anticipated that these technological and sampling innovations along with lengthy periods of pretreatment data and the multi-watershed design will facilitate interpretation of future experimental results.

Lessons learned at Caspar Creek about equipment performance, difficulties of measurement in small streams, importance of pretreatment data, and sampling protocols have been useful for the planning of other watershed-scale studies in California and elsewhere (Rice and others 2004).

The longevity of the Caspar Creek study is due to the commitment shown by the collaborating agencies (U.S. Forest Service and CDF). This has required continuous funding, dedicated field staff and research scientists, and managers willing to conform management activities to research designs.

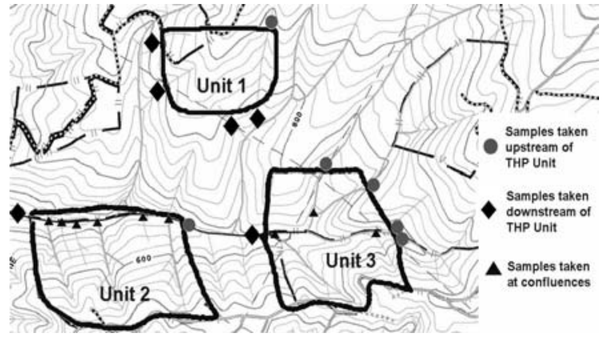

Fig. 3 Forensic monitoring plan utilizing manual turbidity measurements for a timber harvest plan with three harvest units

Turbidity Monitoring at the Project Scale

Project-scale studies have measured turbidity in streams at sites located above, within, and downstream from active timber operations during storms. Although the aim of these studies is to detect management-related effects, downstream measurements integrate all upstream erosion and sediment sources, both natural and anthropogenic. Consequently, in project-scale studies, elevated downstream turbidity triggers field investigations to identify the source(s). As of March 2006, studies had been conducted in Humboldt and Amador Counties (Table 1). In the Elk River and Freshwater Creek watersheds of Humboldt County, these studies are continuing in conjunction with site- and watershed-scale studies conducted by Pacific Lumber Company (PALCO) and others.

Experimental Designs

The basic design at the project scale may be termed ‘‘forensic monitoring.’’ Forensic monitoring relies on manually sampling turbidity upstream, within, and downstream from harvest units during storms to detect existing or harvest-induced sediment sources. There have been a few instances in which automated samplers have been installed downstream from timber harvest projects, but this is not generally done because of costs and other considerations. Manual sampling provides the advantage of spatial representation that cannot be achieved with a single automated sampling station.

Forensic monitoring does not require pretreatment data. Sampling sites are identified on a map of proposed harvest units (Fig. 3), and samples are collected when predetermined criteria are met for antecedent rainfall or storm intensity (3 cm of rain in a 24-hour period was used for the studies in Table 1). Turbidity is sampled at multiple locations above and below management activities during each storm event. Samples are analyzed in the field with a portable turbidimeter following the procedures defined by the manufacturer. If an elevated turbidity signal is noted in a ‘‘below’’ sample, the upstream area is searched to locate the source(s). Adaptive management follow-through includes notifying land managers of the source location so that appropriate remedial actions can be taken in a timely manner.

Data Collection Methods

Storm-based forensic studies utilize manual ‘‘grab’’ sampling in which single or multiple water samples are collected by submerging bottles in the stream. PALCO has had the most experience with forensic studies and has developed a ‘‘standard operating procedure’’ for manual sampling (available on request from Sullivan) to prevent measurement error and minimize variability among sampling personnel. The limitations of manual sampling mainly concern accessibility during storm events and the safety of field personnel.

Case Study Results

PALCO has performed forensic monitoring on its approved THPs in the Elk River and Freshwater Creek watersheds since 2003. The results have not been published to date but they have been presented at public meetings and workshops. In 2003, 417 pairs of samples (above and below harvest units) were collected on active THPs and compared. Of those, 85% showed no significant increase in turbidity (downstream values <120% of upstream values). The 78 sample pairs that showed elevated downstream turbidity levels were classified as ‘‘minor’’ (downstream >140% of upstream) or ‘‘major’’ (downstream >300% of upstream). ‘‘Minor’’ instances were found to be transitory, and no contributing upstream sediment source was located. For ‘‘major’’ instances, inspection of upstream areas led to the identification of 16 sediment sources, 2 of which were attributable to current management. The remaining 14 were due to failing ‘‘legacy’’ roads and skid trails, stream bank erosion, and landslides.

As of March 2006, there was only one other example of forensic monitoring of an active THP. The study was conducted by Regional Water Quality Control Board staff in January and February 2004 and also involved site-level monitoring of stream crossings (CVRWQCB 2004). A newly installed stream crossing was determined to be a sediment source in that study. In addition, there was evidence of erosion and sediment delivery caused by cattle grazing.

Turbidity Monitoring at the Site Scale

Thousands of logging road stream crossings in California have been removed (decommissioned) or upgraded over the past decade (Harris and others in press). After construction, these sites may experience erosion and stream suspended sediment levels may be temporarily increased. These effects generally diminish over time as the site revegetates and the channel achieves a stable morphology. Turbidity monitoring has proven useful for evaluating construction-related impacts at stream crossings and assessing the effectiveness of erosion control methods.

Since 2002, there have been six California studies evaluating the effects of decommissioning or replacing stream crossings (Table 1). These studies have had the common objective of determining the scale and/or the duration of construction impacts on turbidity. Klein (2006) describes a multi-year study in which the objective is to quantify total erosion and sediment delivery from decommissioned crossings. Turbidity monitoring was discontinued in favor of site physical measurements in that study.

Experimental Design

Although turbidity monitoring has only been applied to stream crossings in forest management, it has been applied to a number of other site-specific construction projects in California (e.g., urban development, bridge replacements, flood control structures) as a means of monitoring the effectiveness of mitigation measures (Harris, personal observations). Certain conditions must be met for turbidity monitoring to be used in site-specific applications. First, the treatment or sediment-generating feature must be a ''point source'' such as a culvert or other type of stream crossing, a drainage ditch, or a landslide. Second, where the sampling objective is to determine whether a treated site is experiencing erosion, sample collection times should be based on defined storm or stream flow thresholds that initiate erosion. Third, samples should be collected simultaneously at upstream/downstream or treated/control comparison sites. Fourth, as with any monitoring program, a study plan detailing sample collection and analysis procedures should be developed before treatments begin.

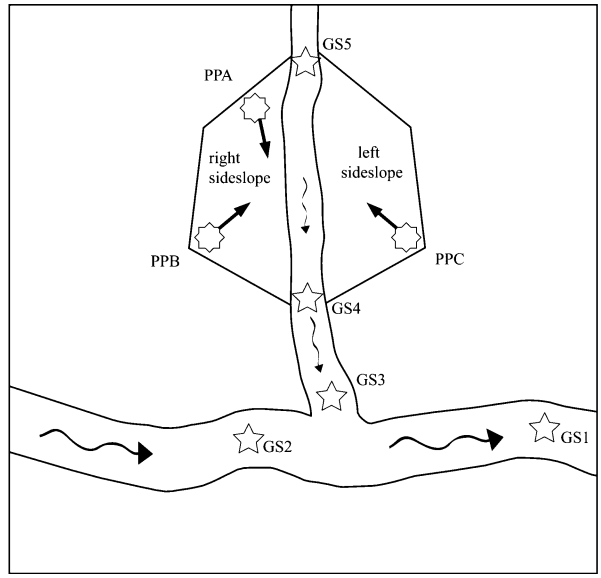

Fig. 4 Grab sampling design for evaluating effects of stream crossing on turbidity. Sampling order proceeds from GS1 to GS5. Permanent photopoints are indicated as PPA, PPB, etc. (Source: Weaver and others 2005, adapted from Klein 2003)

The premise underlying the studies conducted to date is that turbidity levels below or after construction will be elevated relative to turbidity levels above or before construction if erosion control measures are not effective. Differences should be most evident at stream flow peaks, but there may be differences on the rising and falling limbs of the storm hydrograph as well. Pretreatment data are not collected and, to be valid, comparisons are made separately for each storm or stream flow event. Sampling is conducted during a stressing weather event of defined magnitude (3 cm of rain in a 24-hour period is the current criterion for California). It is desirable to sample at least once on the rising and falling limbs of the storm hydrograph and at the peak.

In all studies to date, the sampling design has consisted of taking grab samples immediately below and above the site being studied (Fig. 4). Turbidity samples are either collected and analyzed at laboratory facilities or analyzed in the field using a portable turbidimeter. In the six studies undertaken so far, study duration has varied from 1 year and several storm events to several years with multiple storms.

Analysis of turbidity data involves comparing ''above'' to ''below'' samples at each site for each storm and then comparing the difference to a preselected threshold indicating significant impacts. On the California North Coast, if ''below'' or ''after'' samples are more than 120% of ''above'' or ''before'' samples, as measured in NTUs, the impact is considered significant. This corresponds to the 20% above background sediment limit included in the North Coast Regional Water Quality Control Board's Basin

Plan (NCRWQCB 2005) and is equivalent to water quality standards in other states.

Data Collection

Protocols for grab sample collection have varied between studies (for a copy of standard operating procedures used by PALCO, contact Sullivan). The principal constraints on data collection are 1) catching the peak stream flow, 2) access during adverse and dangerous weather and flow conditions, and 3) simultaneous sampling at multiple locations. Because sampling is triggered when storm intensity and duration criteria have been met, considerable attention must be paid to weather forecasting. Sampling crews must be located nearby so they can respond quickly to storm conditions. Safety is always a key consideration in deploying people during storms.

Case Study Results

None of the six studies have been published, but some reports and presentations have been prepared (Table 1). Study findings have documented general patterns of postconstruction sediment generation at road crossings. These findings include the following: 1) at many sites, turbidity levels below treated crossings will be significantly higher (>120%) relative to levels above the crossing for one or more storms over the course of the winter (Harris, unpublished data, Klein 2003, PALCO 2004); 2) impacts are greatest during early storms and diminish over the winter (Klein 2003); and 3) potential impacts depend on erosion control measures implemented at the sites (PALCO 2004). This last finding is based mainly on the experiences at the Elk River and Freshwater Creek watersheds, where only about 7% of 2300 samples collected at 225 crossings over a 3-year period had downstream turbidity levels more than 20% greater than upstream levels (Sullivan, unpublished data). In a recent study of upgraded stream crossings on PALCO lands in the Elk River watershed channel surveys indicated very minimal erosion in large part due to the extensive erosion control measures applied (Harris and others, in press).

Discussion

California has many watersheds where past and present land uses have caused excessive stream sedimentation. Excessive sedimentation is associated with reduced water quality and reduced habitat quality for aquatic organisms including some anadromous salmonids listed as threatened or endangered by State and Federal laws. The public has committed, through State and Federal legislation and policy, to protecting and restoring endangered species and water quality in California's streams and rivers. This commitment is reflected in regulations and restoration efforts that incur considerable private and public costs.

Although it is certain that past timber harvest practices contributed to current sediment-impaired conditions, there is considerable uncertainty regarding the effectiveness of current forest practice regulations and land management in preventing further degradation. Assuming that timber harvesting continues in California, the need for information is twofold. First, research must address the basic question as to whether or not current forest practices are helping to reverse past degradation and contributing to watershed recovery. Second, land managers need tools for identifying problems as they unfold in areas undergoing timber harvesting so that they can take immediate actions to prevent water quality impacts. Experimental and trend detection studies employing turbidity monitoring at the watershed scale are a means of answering the first question. Forensic and site-scale turbidity monitoring of timber harvest projects and specific activities are suitable tools for an adaptive management approach to timber harvest mitigation.

Over the past few years, several experimental watershed studies have been launched in California. Other similar studies have been initiated in Oregon, Washington, Idaho, Montana, and elsewhere in the world. As results from these studies become available over the next decade, they may be compared with the results obtained from studies of former, less-regulated forest practices. On the California coast, research at Caspar Creek demonstrated that forest practices used in the 1980s, after major revisions of California's Forest Practice Rules, had less impact than the largely unregulated practices used prior to 1973. The future results of new studies may show whether more recent changes in regulations are providing additional reductions in sediment production from timber operations. Future results from nonexperimental monitoring studies at the watershed scale will provide valuable information on trends in watershed conditions and fish population responses to sediment loads.

The difficulties facing public and private organizations conducting California watershed studies are similar to challenges found throughout the world (Cornish 2001, Ice and Stednik 2004, Chappell and others 2004). All studies involving the characterization of sediment in natural streams are confronted with the spatial and temporal variability inherent in sediment transport. These studies are expensive, labor intensive, and can only be done at a limited number of locations. Advances in the technology of turbidity measurement have improved our ability to estimate suspended sediment transport, but have also added to the complexity and expense of these studies.

Additional challenges include maintaining a continuing source of funding given the long time frames necessary to

conduct experiments, establishing statistical validity by sufficient sampling to detect trends and responses, controlling land use for experiments in areas managed by multiple landowners and agencies, and operating complex sampling equipment and procedures in flashy stream environments that are often in remote locations. Most of California's watershed projects experienced difficult start-up periods in which problems were encountered and solved. It is hoped that future proposed studies will be informed by the experiences of these pioneers.

The ultimate challenge will be assimilating, integrating, and presenting the results of the watershed studies being conducted by so many different entities in a manner that contributes to forest management policy. Currently, other than informal information sharing and occasional workshops, there is limited communication between scientists doing watershed studies and even less between scientists and policy-makers. It remains to be seen how policy-makers and the public will access and respond to the results of the current (and potential future) monitoring studies.

In regard to the use of turbidity monitoring as an adaptive management tool, it is instructive to review where that is presently happening in California. Project- and site-scale studies are concentrated in a few watersheds in Humboldt County where timber harvesting is especially controversial. Two of these (Elk River and Freshwater Creek) also have watershed-scale studies. In recent months, Regional Water Quality Control Boards in the Sierra Nevada and central California coast have developed regulatory procedures related to timber harvesting that may require turbidity monitoring to determine whether water quality standards are being met. As a consequence of these actions, it is very likely that forensic and site-scale turbidity monitoring will expand to these regions in the future. If linked to an adaptive management response, turbidity monitoring during stressing weather and stream flow events will have immediate benefits to water quality when emerging problems are promptly identified and mitigated. If monitoring is just considered a regulatory exercise, the opportunity for directly improving forest management practices will be lost.

There are study design and implementation issues related to turbidity monitoring at any scale. Many published sources of information are available for watershed-scale studies (see Literature Cited). There are no published accounts of using turbidity measurements in forensic monitoring of forest management projects or specific activities. Lane and Sheridan (2002) used continuous turbidity monitoring at a single newly installed stream crossing to estimate sediment production associated with the crossing. That approach, however, is neither feasible nor desirable in California, where hundreds of stream crossings are upgraded or removed every year during timber-harvesting operations. Most of the research on road and timber-harvest sediment production is based on physical measurements or modeling (Croke and others 1999, Croke and Mockler 2001, Fransen and others 2001, MacDonald and others 2001, Gomi and others 2004, Sidle and others 2004, Croke and Nethery 2006, Forsyth and others 2006). Neither of these approaches provides the advantage of forensic monitoring, as described here, which can elicit an immediate remedial response.

Outside the context of adaptive management, turbidity measurement may not be the most appropriate method to assess the impacts of timber harvesting and transportation systems. If a goal of assessment is to determine the total sediment delivery from a project or site relatively inexpensively, it will be more appropriate to use sediment traps, basins, or fences to measure sediment production (MacDonald and others 1991, Robichaud and Brown 2002, MacDonald and others 2004) or to measure erosion voids after stressing weather events (Madej 2001, Klein 2003, 2006, Pacific Watershed Associates 2005, Harris and others in press). Post-hoc studies of erosion voids can determine the net soil loss at treated sites over some time period after soil-disturbing activities. These studies can also provide estimates of total sediment yield in cases where turbidity monitoring is either not appropriate or too costly.

Conclusions

Turbidity monitoring to evaluate impacts of forest management on suspended sediment loads in California streams has increased dramatically over the past several years. This increase is due to a combination of regulatory concerns and improvements in technology and operating procedures. Turbidity monitoring can be applied at the watershed, project, and site scales, with the approach at each scale depending on monitoring objectives, costs, and other factors. Generally, relatively costly and technologically complex automated monitoring should be confined to well-funded and well-designed trend and experimental studies at the watershed scale. Manual sampling approaches at the project and site scales are well suited for adaptive management and forensic monitoring to identify sediment sources and to mitigate their impacts. Monitoring at any scale promises to improve both the regulation and environmental excellence of forest practices in California.

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References

Anderson CW (2004) Turbidity. U.S.D.I. Geological Survey Techniques of Water-Resources Investigations, Book 9, Chapter A6, section 6.7. Available at: http://www.water.usgs.gov/owq/FieldManual/Chapter6/6.7_contents.html

Ankcorn PD (2003) Clarifying turbidity: the potential and limitations of turbidity as a surrogate for water-quality monitoring. In: Hatcher KJ (ed) Proceedings of the 2003 Georgia water resources conference, 23–24 April 2003. University of Georgia, Athens, GA

Barber TJ, Birkas A (2005) Garcia River trend and effectiveness monitoring: spawning gravel quality and winter water clarity in water years 2004 and 2005, Mendocino County, California. Final Report prepared for the Mendocino County Resource Conservation District. Ukiah, California, 70 pp

Beschta RL (1980) Turbidity and suspended sediment relationships. In: Proceedings of the 1980 American Society of Civil Engineers symposium on watershed management, 21–23 July 1980. Boise, ID, pp 271–282

Beschta RL (1987) Conceptual models of sediment transport in streams. In: Thorne CR, Bathurst JC, Hey RD (eds.), Sediment transport in gravel-bed rivers. John Wiley and Sons, New York, pp 387–419

Bisson PA, Bilby RE (1982) Avoidance of suspended sediment by juvenile coho salmon. North Am J Fisheries Manage 2:371–374

Brown WM, Ritter JR (1971) Sediment transport and turbidity in the Eel River basin, California. U.S.D.I. Geological Survey Water Supply Paper 1986, 70 pp

Cafferata PH, Munn JR (2002) Hillslope monitoring program: monitoring results from 1996 through 2001. Monitoring Study Group Final Report prepared for the California State Board of Forestry and Fire Protection. Sacramento, CA, 114 pp Available at: http://www.bof.fire.ca.gov/pdfs/ComboDocument_8_.pdf

Central Valley Regional Water Quality Control Board (CVRWQCB) (2004) Turbidity monitoring at South Spur 1 timber harvest plan, Amador County. Regional Water Quality Control Board, Central Valley Region, Sacramento Office Staff Report, 27 pp

Chappell NA, Douglas I, Hanapi JM, Tych W (2004) Sources of suspended sediment within a tropical catchment recovering from selective logging. Hydrol Processes 18:685–701

Cornish PM (2001) The effects of roading, harvesting and forest regeneration on streamwater turbidity levels in a moist eucalypt forest. Forest Ecol Manage 152:293–312

Croke J, Mockler S (2001) Gully initiation and road-to-stream linkage in a forested catchment, southeastern Australia. Earth Surface Processes Landforms 26:205–217

Croke J, Nethery M (2006) Modelling runoff and soil erosion in logged forests: scope and application of some existing models. Catena 67:35–49

Croke J, Hairsine P, Fogarty P (1999) Sediment transport, redistribution and storage on logged forest hillslopes in south-eastern Australia. Hydrol Processes 13:2705–2720

Davies-Colley RJ, Smith DG (2001) Turbidity, suspended sediment, and water clarity: a review. J Am Water Resources Assoc 37:1085–1100

Eads R, Lewis J (2002) Continuous turbidity monitoring in streams of northwestern California. In: Gysson GD, Gray JR (eds) Proceedings of the turbidity and other sediment surrogates workshop. 30 April–02 May 2002, Reno, Nevada, U.S.D.I. Geological Survey Circular 1250

Edwards TK, Glysson GD (1999) Field methods for measurement of fluvial sediment. U.S.D.I. Geological Survey Techniques of Water-Resources Investigations, book 3, chapter 2. http://www.water.usgs.gov/pubs/twri/twri3-c2/

Elliot WJ, Robichaud PR, Luce CH (1995) Applying the WEPP erosion model to timber harvest areas. In: Proceedings of the American Society of Civil Engineers conference on watershed management, August 1995, San Antonio, TX, pp 83–92

Forsyth AR, Bubb KA, Cox ME (2006) Runoff, sediment loss and water quality from forest roads in a southeast Queensland coastal plain *Pinus* plantation. Forest Ecol Manage 221:194–206

Fransen PJB, Phillips CJ, Fahey BD (2001) Forest road erosion in New Zealand: overview. Earth Surface Processes Landforms 26:165–174

Gippel CJ (1995) Potential of turbidity monitoring for measuring the transport of suspended solids in streams. Hydrol Processes 9:83–97

Gomi T, Sidle RC, Swanston DN (2004) Hydrogeomorphic linkages of sediment transport in headwater streams, Maybeso Experimental Forest, southeast Alaska. Hydrol Processes 18:667–683

Graham Matthews and Associates (GMA) (2004) Project scale effectiveness monitoring for the South Fork Wages Creek Watershed. Final Study Plan prepared for Campbell Timberland Management and the California Department of Forestry and Fire Protection. Version 2.0, November 2004. Weaverville, CA. 46 pp Available at: http://www.bof.fire.ca.gov/pdfs/SFWages_EffectivenessProposal_Nov2004.pdf

Harris RR, Gerstein JM, Cafferata PH (in press) Changes in stream channel morphology caused by replacing road-stream crossings on timber harvesting plans in northwestern California. West J Appl Forestry

Henley WF, Patterson MA, Neves RJ, Lemly AD (2000) Effects of sedimentation and turbidity on lotic food webs: a concise review for natural resource managers. Rev Fisheries Sci 8:125–139

Hunsaker CT, Eagan SM (2003) Small stream ecosystem variability in the Sierra Nevada of California. Pages 716–721 In: Renard KG, McElroy SA, Gburek WJ, Canfield HE, Scott RL (eds.) First interagency conference on research in the watersheds, 27–30 October 2003. U.S. Department of Agriculture, Agricultural Research Service. Available at: http://www.fs.fed.us/psw/programs/snrc/water/kingsriver/documents/Hunsaker.pdf

Ice GG, Stednick JD (eds) (2004) A century of forest and wildland watershed lessons. Society of American Foresters, Bethesda, MD

James C (2004) Water quality monitoring proposal for the Judd Creek watershed. Draft Study Plan. Sierra Pacific Industries, Anderson, CA, 11 pp http://www.bof.fire.ca.gov/pdfs/Judd%20Creek%20Final_Prospectus_MSG_maps.pdf

Kelsey HM (1980) A sediment budget and an analysis of geomorphic process in the Van Duzen River basin, north coastal California, 1941–1975: summary. Geol Soc Am Bull 91:190–195

Klein R (2003) Erosion and turbidity monitoring report: Sanctuary Forest stream crossing excavations in the Upper Mattole River basin, 2002–2003. Final Report prepared for the Sanctuary Forest, Inc., Whitethorn, CA, 34 pp. Available at: http://www.bof.fire.ca.gov/pdfs/RKleinSanctSept2003.pdf

Klein R (2006) Erosion and turbidity monitoring in Lost Man Creek, Redwood National and State Parks: annual report for water year

2005 and retrospective on water years 2003–2005. Redwood National and State Parks. 38 pp
Lane PNJ, Sheridan GJ (2002) Impact of an unsealed forest road stream crossing: water quality and sediment sources. Hydrol Process 16:2599–2612
Lewis J (1996) Turbidity-controlled suspended sediment sampling for runoff-event load estimation. Water Res Res 32:2299–2310
Lewis J (1998) Evaluating the impacts of logging activities on erosion and sediment transport in the Caspar Creek watersheds. Pages 55–69 In: Ziemer RR (technical coordinator) Proceedings of the conference on coastal watersheds: the Caspar Creek story, 6 May 1998 Ukiah, CA. General Technical Report PSW GTR-168. Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture. Available at: http://www.fs.fed.us/psw/publications/documents/gtr-168/07lewis.pdf
Lewis J (2002) Estimation of suspended sediment flux in streams using continuous turbidity and flow data coupled with laboratory concentrations. In: Gysson GD, Gray JR (eds.) Proceedings of the turbidity and other sediment surrogates workshop. 30 April–02 May 2002, Reno, Nevada, U.S.D.I. Geological Survey Circular 1250
Lewis J, Eads R (2001) Turbidity threshold sampling for suspended sediment load estimation. In: Proceedings of the 7th federal interagency sedimentation conference, 25–29 March 2001, Reno, Nevada
Lewis J, Mori SR, Keppeler ET, Ziemer RR (2001) Impacts of logging on storm peak flows, flow volumes and suspended sediment loads in Caspar Creek, California. 85–125 Pages In: Wigmosta MS, Burges SJ (eds) Land use and watersheds: human influence on hydrology and geomorphology in urban and forest areas. Water Science and Application Volume 2, American Geophysical Union, Washington, D.C. Available at: http://www.fs.fed.us/psw/publications/lewis/CWEweb.pdf
MacDonald LH, Smart AW, Wissmar RC (1991) Monitoring guidelines to evaluate the effects of forestry activities on streams in the Pacific Northwest and Alaska. EPA 910/9-91-001, U.S. Environmental Protection Agency, Region X, Seattle, WA, 166 pp
MacDonald LH, Sampson RW, Anderson DM (2001) Runoff and road erosion at the plot and road segment scales, St. John, US Virgin Islands. Earth Surface Processes Landforms 26:251–272
MacDonald LH, Coe D, Litschert S (2004) Assessing cumulative watershed effects in the central Sierra Nevada: hillslope measurements and catchment-scale modeling. In: Stine P, Murphy D (eds) Proceedings of the Sierra Nevada science symposium, 7–10 October 2002, Kings Beach, CA, U.S.D.A.-Forest Service General Technical Report. PSW-GTR-193, Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture, pp 149–157
Madej MA (1999) Temporal and spatial variability in thalweg profiles of a gravel-bed river. Earth Surface Processes Landforms 24:1153–1164
Madej MA (2001) Erosion and sediment delivery following removal of forest roads. Earth Surface Processes Landforms 26:175–190 Available at: http://www.werc.usgs.gov/redwood/esplroads.pdf
Manka P (2005) Suspended sediment yields in tributaries of Elk River, Humboldt County, California. Master of Science Thesis, Humboldt State University, Arcata, California, 91 pp. Available at: http://www.humboldt.edu/~egr2/documents/MankaThesis.pdf
North Coast Regional Water Quality Control Board (NCRWQCB) (2005) Basin Plan. Water Quality Objectives, Section 3. Santa Rosa, California. Available at: http://www.waterboards.ca.gov/northcoast/programs/basinplan/083105-bp/3_water_quality_objectives.pdf
Pacific Lumber Company (PALCO) (2004) Report of waste discharge: Elk River. Final Report dated October 12, 2004 submitted to the North Coast Regional Water Quality Control Board, Santa Rosa, California, pp 179
Pacific Watershed Associates (PWA) (2005) Evaluation of road decommissioning in the Elk River watershed, Humboldt County, California. Final Report prepared for the Pacific Lumber Company, Scotia, California. Pacific Watershed Associates, Arcata, California, pp 29
Rehg KJ, Packman AI, Ren J (2005) Effects of suspended sediment characteristics and bed sediment transport on streambed clogging. Hydrol Processes 19:413–427
Rice RM, Ziemer RR, Lewis J (2004) Evaluating forest management effects on erosion, sediment, and runoff: Caspar Creek and northwestern California. In: Ice GG, Stednick JD (eds) A century of forest and wildland watershed lessons. Society of American Foresters, Bethesda, MD, pp 223–238
Robichaud PR, Brown RE (2002) Silt fences: an economical technique for measuring hillslope erosion. General Technical Report RMRS-GTR-94. Fort Collins, CO; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 24 pp
Sidle RC, Sasaki S, Otsuki M, Noguchi S, Nik AR (2004) Sediment pathways in a tropical forest: effects of logging roads and skid trails. Hydrol Processes 18:703–720
Stewart-Oaten A, Murdoch WW, Parker KR (1986) Environmental impact assessment: ''pseudoreplication'' in time? Ecology 67:929–940
Tate KW, Dahlgen RA, Singer MJ, Allen-Diaz B, Atwill ER (1999) Timing, frequency of sampling affect accuracy of water-quality monitoring. California Agric 53:44–48
United States Environmental Protection Agency (USEPA) (1999) Guidance manual for compliance with the interim enhanced surface water treatment rule: turbidity provisions. EPA 815-R-99-010. Available at: http://www.epa.gov/safewater/mdbp/mdbptg.html
Wagner RJ, Boulger RW, Jr, Oblinger CJ, Smith BA (2006) Guidelines and standard procedures for continuous water-quality monitors: Station operation, record computation, and data reporting. U.S. Geological Survey Techniques and Methods 1–D3. U.S. Geological Survey, Reston, Virginia. 51 pp and 8 attachments. Available at: http://pubs.water.usgs.gov/tm1d3
Walters CJ, Collie JS, Webb T (1988) Experimental designs for estimating transient responses to management disturbances. Can J Fisheries Aquat Sci 45:530–538
Weaver WW, Gerstein JM, Harris RR (2005) Monitoring the effectiveness of upland restoration. University of California, Center for Forestry, Berkeley, CA, 100 pp. Available at: http://www.forestry.berkeley.edu/comp_proj/dfg.html
Ziegler AC (2003) Issues related to use of turbidity measurements as a surrogate for suspended sediment. Pages 16–18 In: Gysson GD, Gray JR (eds.) Proceedings of the turbidity and other sediment surrogates workshop. 30 April–02 May 2002, Reno, Nevada, U.S. Geological Survey Circular 1250. Available at: http://www.water.usgs.gov/osw/techniques/TSS/ZieglerT.pdf
Ziemer RR (technical coordinator) (1998) Proceedings of the conference on coastal watersheds: the Caspar Creek story. 6 May 1998; Ukiah, California. General Technical Report PSW GTR-168. Albany, California: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture; 149 pp. Available at: http://www.fs.fed.us/psw/publications/documents/gtr-168/gtr-168-pdfindex.html